

Sustained propagation and topological excitation control in polariton superfluid

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We present a simple setup to compensate for loss in a polariton superfluid. It allows for a macroscopic extension of a resonantly driving polariton superfluid at a minimal energetic cost. Moreover, this setup takes full advantage of the optical bistability present in these system and leads to a significant release of the phase pressure effect due to resonant driving. This release, together with the macroscopic extension provided, give rise, in presence of a localized potential barrier, to a vortex stream. We numerically study in detail how the intensity of the coherent driving supporting the superfluid flow modifies the properties of the vortices and show that in some regime standard hydrodynamics does not apply for this driven-dissipative fluid. Moreover, taking advantage of this effect we illustrate how the path of these topological excitations can be controlled.

The control and manipulation of quantum states of matter is a challenging goal in modern physics. Among recent developments, the discovery of quantum states, such as Bose-Einstein condensates and superfluids, in solid-state quasi-particles like exciton polaritons opens new perspectives [1, 2]. In a semiconductor microcavity within which are embedded quantum wells with an excitonic transition resonant with the cavity mode, recent technological developments allow for reaching the strong coupling regime, where the system eigenmodes are an indistinguishable mix of excitons and cavity photons, called polaritons. The unique balance between the dissipative nature of these quasi-particles and their non-linear dynamics leads to the generation of a superfluid of polaritons [3].

One way to observe exciton polaritons is to quasi-resonantly drive the system with a laser field. For homogenous excitation or a large enough excitation spot, this gives rise to an optical bistability for slightly blue-shifted laser field [4]. The associated hysteresis delimits two different regimes: (i) a linear regime for weak driving field, where elastic diffusion can take place; and (ii) a superfluid regime for strong driving field, where such scattering processes cannot take place anymore because of the non-linearity. Several peculiar properties of superfluids were predicted and observed recently in polaritonic system, e.g., frictionless propagation [2], and vortex pair and soliton generation [5–8], heralding a new way to study hydrodynamics of superfluids.

In the present article we focus on neither of these two regimes, but on an intermediate one: the bistable regime. As we will show, the bistable regime exhibits rich dynamical features, allowing for compensation of the dissipation inherent to these fluids, and thus for macroscopically extended the propagation length of the superfluid at low energetic cost. Moreover, as was shown in Ref. [7], resonant driving tends to impose a phase on the generated superfluid, inhibiting the formation of topological excitations such as vortices or solitons. Consequently, an engineered driving profile is required to observe such fundamental excitations [5, 6, 8], making

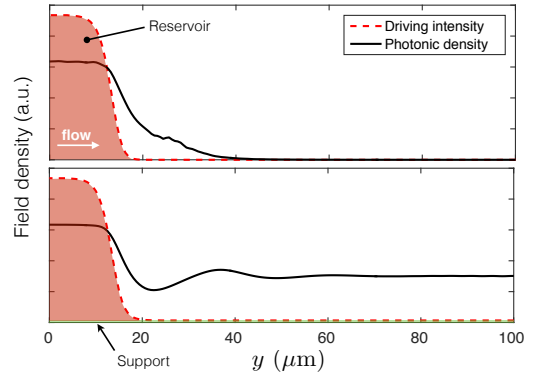


Figure 1. Steady state photonic density (solid black curves) of a polariton superfluid and corresponding driving profile (red dashed curves). The upper panel represents the unsupported flow ($I/I_+ = 0$) and the lower panel the supported flow ($I/I_+ = 0.08$, point A in Fig. 2). The colored region delimits the reservoir (in red) and the support (in green) driving. The parameters used are: $\hbar\omega_c(\mathbf{k} = \mathbf{0}) = 1602\text{meV}$, $\hbar\omega_x(0) = 1600\text{meV}$, $\hbar\gamma_x = \hbar\gamma_c = 0.05\text{meV}$, $\hbar\Omega_r = 2.5\text{meV}$ and $\hbar g = 0.01\text{meV}$. The driving field is such that $\Delta = \hbar\omega_p - \hbar\omega_{LP}(\mathbf{k} = \mathbf{0}) = 1\text{meV}$ and $|\mathbf{k}_p| = (0, 1)^T \mu\text{m}^{-1}$. The simulations are performed on a grid of 128×256 .

thorough hydrodynamic studies difficult. In the present paper we show how within the bistable regime this pressure on the phase is reduced, allowing for the generation and propagation of vortices. The combination of a macroscopic enhancement of the propagation length together with small phase pressure effect allows for a first detailed hydrodynamic analysis of vortex-pair dynamics in a superfluid. The role played by the resonant driving unique to these out-of-equilibrium superfluids is crucial and allows, as we will see, for a fine control of vortex-pair properties. Prediction obtained by means of standard equilibrium hydrodynamics are also tested; by showing that they do not necessary apply here we reveal a brand new field of driven-dissipative hydrodynamics.

In order to explore the bistable regime we consider

two driving fields with identical frequency ω_p and in-plane wave-vector \mathbf{k}_p . One driving field of high intensity is localized and is used to create a reservoir of polaritons superfluid. The second driving field, homogenous in time and space, acts as a support field and is of weak intensity. We use the second, support-driving, field as a control parameter to explore the different regimes from linear to superfluid, passing through the bistable regime. The time-evolution in these conditions is described by a generalized Gross-Pitaevskii equation [3]:

$$i\partial_t \begin{pmatrix} \Psi_c(\mathbf{x}, t) \\ \Psi_x(\mathbf{x}, t) \end{pmatrix} = \hbar \begin{pmatrix} F_s + F_r(\mathbf{x}) \\ 0 \end{pmatrix} e^{-i(\mathbf{k}_p \cdot \mathbf{x} - \omega_p t)} + \hbar \begin{pmatrix} \omega_c(-i\nabla) + V(\mathbf{x}) - i\frac{\gamma_c}{2} & \Omega_r \\ \Omega_r & \omega_x^0 + g|\Psi_x(\mathbf{x}, t)|^2 - i\frac{\gamma_x}{2} \end{pmatrix} \times \begin{pmatrix} \Psi_c(\mathbf{x}, t) \\ \Psi_x(\mathbf{x}, t) \end{pmatrix}, \quad (1)$$

where $\Psi_{c(x)}(\mathbf{x}, t)$ represents the cavity (exciton) field, $\hbar\omega_c(-i\nabla)$ is the energy dispersion of the cavity modes, and $\hbar\omega_x^0$ corresponds to the exciton dispersion assuming infinite mass. $\gamma_{c(x)}$ is the decay rate of the cavity (exciton) modes, and g is the exciton-exciton interaction. $V(\mathbf{x})$ is the photonic potential. The first term of Eq.(1) refers to the driving. We use $F_r(\mathbf{x})$ to represent a reservoir driving and F_s the support driving.

We illustrate the considered setup in Fig. 1, presenting jointly the steady-state photonic density of a polariton superfluid flowing from left to right (black curves) in a perfect cavity ($V = 0$) for the total driving profile represented in red dashed curves. In the upper panel, only the reservoir driving $F_r(\mathbf{x})$ acts on the system (i.e., $F_s = 0$); it creates a superfluid polariton reservoir where the density falls rapidly outside driven region, shown in red. As the lower panel of Fig. 1 highlights, if the superfluid is supported even slightly along its propagation ($F_r \gg F_s \neq 0$, shown in green), the polariton flow is maintained with a macroscopic density. The modulations observe nearby the reservoir are due to the reservoir driving spacial profile. Even with more than one order of magnitude between the two driving field intensities, the polaritonic density is maintained and the superfluid can therefore propagate macroscopically.

This macroscopic enhancement of the superfluid propagation is a direct consequence of optical bistability. This phenomenon is typical for quasi-resonantly driven Kerr non-linear media [9]. Many rich phenomena are related to this effect such as a large variety of solitonic solution [10]. It is characterised by two distinct critical driving intensities, I_+ and I_- , ($I_- < I_+$) in-between which the system is bistable and can be either in linear regime or in a non-linear/superfluid regime. This exact feature is clearly visible in Fig. 2 where we plot the polariton density [11] as a function of the support driving intensity ($I = |F_s|^2$). Here the red curve corresponds to only the support driving whereas the blue curve to the support and reservoir driving. If we trigger the superfluid regime with a local (reservoir) driving we maintain

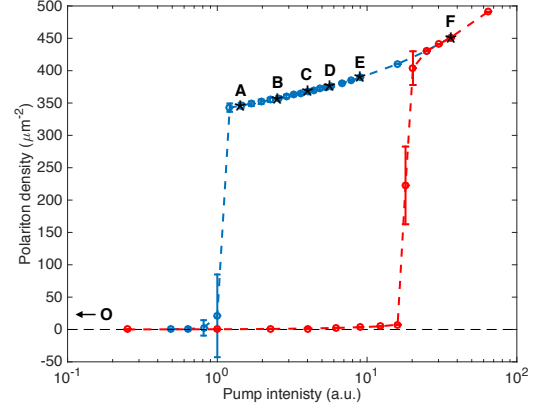


Figure 2. Polariton density as a function of pump intensity. The red dashed line with dots correspond to steady states obtained only in the presence of the support driving ($F_r = 0$), as the blue one represent the case with jointly the reservoir and support driving on ($F_r \neq 0$). The labeled black stars refer to the panels of Fig. 3. Other parameters are identical as in Fig. 1.

the superfluid even with very low support. Combining trigger driving and support driving has been previously explored in polaritonic systems in a context bright soliton written-erasure protocol [12] as considering "light bullet" propagation [13], also mixed with spin degree of freedom [14] (neglected here). In contrast, here we will use this scheme to explore the hydrodynamic properties of the upper branch of this optical bistability.

In order to probe superfluidity and to reveal its characteristics, we place a localized photonic potential barrier in the stream of the fluid just below the reservoir region ($V \neq 0$). Similar scheme has been used to identify the different superfluid hydrodynamics regimes [7]. It allows for a total release of the phase pressure due to resonant driving. Depending on the flow speed and speed of sound ($c_s = \sqrt{mgn/\hbar}$ with m the effective mass and n the polariton density), different hydrodynamic regimes can be observed, associated to the appearance, or lack, of topological excitations [5, 6]. Here we focus on the turbulent regime where pairs of vortices nucleate at the edge of the defect and follows the superfluid stream. In Fig. 3 panel O, we show a snapshot of the polaritonic density for this exact setup with no support driving provided. The reservoir is localized in the upper part where the figure is saturated; below this we can distinguish the photonic defect. The other panels of Fig. 3 correspond to sustained propagation using support whose intensity increases from panels A to F (the labels refer to Fig. 2). Firstly we see, as described in Fig. 1, that the presence of support driving allows for a superfluid propagating over more than 100 μm . Moreover, from panel A to F we clearly see a vortex stream starting from the potential barrier and following the stream whose characteristic changes as the support driving increases. Vortices and antivortices (with inverted circulation) are marked, respectively, with red stars and blue circles. Their density

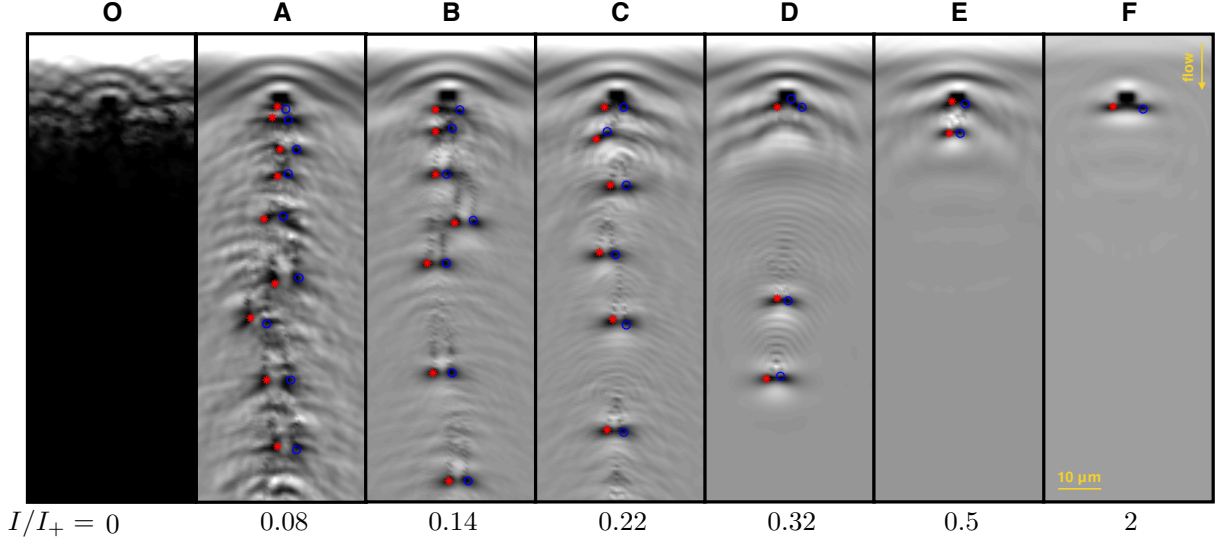


Figure 3. Density profile (snapshot) of polariton superfluid propagating through a photonic defect for different support intensities (increasing from left to right). The label of each panel refers to a point on Fig. 2, and the relative intensity of the support driving is indicated at the bottom of each panel. The red stars and blue circles indicate, respectively, vortices and antivortices. Other parameters are identical to in Fig. 1.

reduces as the support increases. In Supplementary Material [11] a video is presented showing dynamical evolution over 0.5 ns, illustrating also that the vortex speed decreases when the support increases. Those different effects arise from the competition taking place between phase imposed by the support driving field, which is homogeneous and related to a given in-plan wave vector \mathbf{k}_p and phase of the vortices, rotating around their cores. Increasing the support intensity, local phase modulation tends to be suppressed.

Before quantifying this effect we discuss two features of interest revealed by these simulations. First, wavefronts of Cherenkov type are present between the reservoir and the potential barrier. They appear because the density profile close to the reservoir is not monotonic (see lower panel in Fig. 1), leading to a local supersonic regime characterized by the Cherenkov wavefronts. Upon passing the potential barrier the density stabilizes such as to be in a superfluid regime, and accordingly the Cherenkov wavefront fades away [7, 16]. Secondly, as is visible in the video [15], a vortex seems to be trapped beside the potential barrier. Because the potential barrier is purely photonic, the nature of the fluid in the potential barrier's shadow, mostly excitonic, is more favorable to phase modulation and so to the presence of vortices.

In order to explore more quantitatively the vortex stream properties as a function of the support intensity, we present in Fig. 4 (upper panel) the emission rate of vortices propagating. This rate decreases strongly as the support intensity increases, until vortices no longer propagate, which happens even if we are still within the bistable region (panel E). The emission rate scale inversely with the intensity of support driving. The sup-

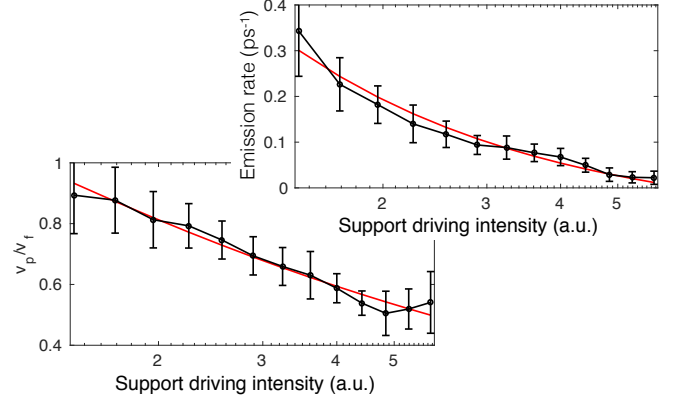


Figure 4. Impact in the vortex stream of the support driving. The top panel represents the emission rate of vortices propagating and the lower panels the vortex speed v_p (normalized with respect to the fluid flowing speed v_f). In each panel the black dotted curve corresponds to statistical data extracted for simulations identical to the ones shown in Fig. 3 and the video [15]. The red curves are fits to the data. Other parameters are identical to those in Fig. 1.

port driving inhibits the propagation of vortices, forcing them to recombine near the potential barrier. Notice that the fluid velocity is constant over this range and related to the in-plan wave \mathbf{k}_p of the reservoir and support driving, while the change in density is of about 10%. Another property of these topological excitations that is strongly modulated is their speed as represented in the lower panel of Fig. 4. Their speed is reduced by 50% for increasing support. For a support intensity close to the lower limit of the bistability I_- we find vortices flowing at almost the same speed as the superfluid,

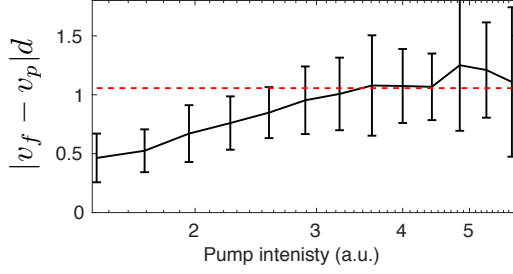


Figure 5. Product of vortex speed v_p with pair separation d as a function of the support intensity. The black dotted curve corresponds to data extracted from the simulations and the red dashed line corresponds to \hbar/m .

while for an intensity close to the higher limit I_+ , their speed is half the fluid speed. Interestingly the vortex speed scales with the inverse of the amplitude of the driving field and not with its intensity. Instead of pushing the vortices accordingly to the momentum direction imposed by the support field, the support driving field slows them down; it acts as a friction force on vortex pairs. Connected to this slowing down we observe that the pair separation distance is also affected, reducing as the support increases. By controlling the support intensity provided to the polariton superfluid we can control such properties of the vortex streams.

Propagation of vortex pairs in liquids is a well-studied phenomenon [17]. In a conventional fluid, the relative speed $|v_f - v_p|$ of a vortex-antivortex pair evolves as $|v_f - v_p| = \kappa/2\pi d$ with κ the vortex circulation. In a superfluid the circulation around the vortex core is quantified as $\kappa = 2\pi\hbar/m$ [18]. Consequently the product of the pair separation d with the vortex speed should be equal to \hbar/m . We present in Fig. 5 this value (red dashed line), which is independent of the support driving, together with the product $|v_f - v_p|d$ gathered from the simulations (black error bars). Fig. 5 clearly shows that both results coincide for strong support. Nevertheless for smaller support (from $I/I_+ \approx 0.15$ to I_-) the deviation is significant. This out-of-equilibrium superfluid has hydrodynamic properties that deviate significantly from standard conservative fluids.[19]

We shown so far how this phase pressure produced by the support driving allows to control vortex pair properties. We will now illustrate how the same effect can be used to manipulate the propagation path of the vortex pairs. In Fig. 6 we represent the polaritonic density but averaged in time. Upon averaging over time, the vortex stream will appear as a low-density line, where the local decrease of the density is directly proportional to the emission rate. To the reservoir and the support driving we add a third localized continuous driving indicated by the red dashed lines and star in Fig. 6. The idea is to apply local pressure to the fluid phase such as to inhibit locally the presence of vortices and force the vortex stream to deviate. In the left panel we add a vertical localized driving with a gaussian spatial profile but

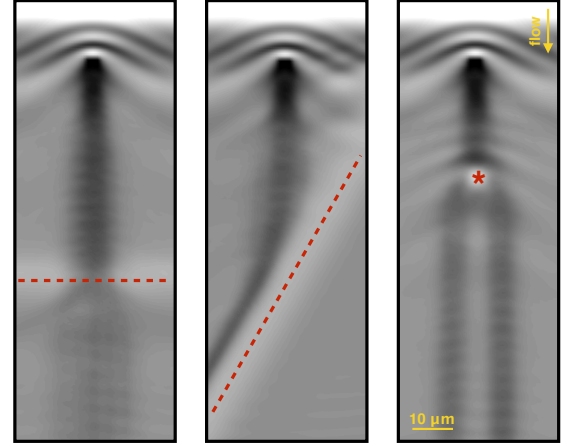


Figure 6. Time integrated density profile of a polariton superfluid with support driving ($I/I_+ = 0.14$) in the presence of an extra localized driving of high intensity highlighted by the red dashed lines and star. The extra driving has a gaussian profile of width $\sigma = 2\mu\text{m}$ and the time integration is taken over 0.5 ns. Other parameters correspond to Fig. 1

otherwise identical properties to the two other driving fields. As a result we obtained a diffused vortex stream. The dark region broadens and become grayer. Instead if this localized driving is tilted with sufficient angle as in the middle panel of Fig. 6, the stream is directed along the driving line. Finally, if the driving is now focused into the stream we can split it in two, as is visible in the right panel of Fig. 6. Notice that the resulting stream is always here composed of vortex pairs.

To conclude, we numerically study in detail the interaction between a support driving field and the propagation of a polariton superfluid. We demonstrate how the propagation length of such a superfluid can be macroscopically enhanced for low energetic cost by taking advantage of optical bistability. Using this setup we report that the release of the phase pressure induced by a support resonant driving is such that formation of topological excitations as vortices is possible. Moreover we show that by modulating the support, the properties of a vortex stream generated by a localized potential barrier can be manipulated significantly. Based on a thorough analysis of the properties of the resulting vortices we also demonstrated that in this regime of sustained superfluid propagation the hydrodynamic behavior of the vortex stream does not match standard conservative hydrodynamics. Finally we considered the same phase pressure effect to control the path of the vortex stream. This work is crucial since it allows for a true study of hydrodynamics of superfluids within an experimentally feasible setup. Moreover it also sheds light on the phase pressure mechanism in the context of an out-of-equilibrium superfluid and uses this same mechanism to achieve fine control of topological excitations taking place within these fluids.

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